Forty-eight Years of Rice Improvement in Texas since the Release of Cultivar Bluebonnet in 1944

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ABSTRACT

Information on the contribution of plant breeding to changes in yields and other agronomic traits is useful for optimizing selection gains; thus, this study aimed to determine the contribution of Texas rice (*Oryza sativa* L.) breeding to changes in cultivars released during the 48 yr since the release of 'Bluebonnet' in 1944. Twenty-three cultivars were evaluated in three environments and two N levels. Days to heading, plant height, whole and total milled rice percentages, and grain yield were measured. Significant variation among cultivars was found for all traits evaluated, while N affected all traits except milled rice. There was a linear decrease in days to heading in cultivars released from 1944 to 1992. Plant height decreased at 1.28 and 1.10 cm yr^{-1} for the 190 and 95 kg ha^{-1} N levels, respectively, mainly due to the incorporation of the semidwarf gene in many cultivars starting in 1981. Plant heights of recently released cultivars were more stable across N levels and less susceptible to lodging. Although whole and total milled rice percentages increased at 0.06 and 0.03% yr^{-1}, respectively, environmental factors limited their genetic advances. Grain yield increased at 42.0 and 26.3 kg ha^{-1} yr^{-1} under the 190 and 95 kg ha^{-1} N levels, respectively, demonstrating that newer releases responded well to higher N. These show the remarkable progress in the Texas rice breeding program from 1944 to 1992.

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Abbreviationa: IRRI, International Rice Research Institute; URRN, Uniform Regional Rice Nursery.

The contribution of crop improvement to yield increases has been studied in wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* subsp. *vulgare* L.), oat (*Avena sativa* L.), maize (*Zea mays* L.), smooth bromegrass (*Bromus inermis* Leyss.), cassava (*Manihot esculenta* L.), tobacco (*Nicotiana tabacum* L.), and rice (*Oryza sativa* L.) (Tollenaar, 1989; Babcock and Foster, 1991; Feil, 1992; Casler et al., 2000; Peng et al., 2000; Abeledo et al., 2003; Kawano, 2003; Nersting et al., 2006). Most of the studies showed increasing yield trends. Often, the increases were attributed to improvement in harvest index, which is associated with traits such as plant height, increases in biomass, or the combination of dry matter accumulation and higher harvest index. In rice, Peng et al. (2000) evaluated 12 cultivars developed since 1966 at the International Rice Research Institute (IRRI), and grain yield was regressed on the year of release. Results indicated an annual gain of 75 to 81 kg ha^{-1}, equivalent to an increase of 1% yr^{-1}. The latest cultivar had similar yield with the first released, 'IR8' at 9 to 10 t ha^{-1}, and it was presumed that the 1% increase may not be genetic gain in yield potential. Before 1980, changes in rice yield trends were the result of the improvement of harvest index, but it was total biomass that determined yield after 1980. In barley developed in Argentina from 1944 to 1998, yield potential was constant at 5.25 t ha^{-1} until 1970, and it increased at

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41 kg ha^{-1} yr^{-1} afterward (Abeledo et al., 2003). In the 100 yr of oat breeding in Norway, shorter plant height, earlier heading, and higher harvest index than landraces, and loss of agronomic and genetic diversity in cultivar release after 1940 were reported (Nersting et al., 2006).

The rice industry of southeast Texas started with 71 ha planted at Beaumont in 1892, and over 3500 ha were harvested by 1899 (Texas Agricultural Experiment Station, 1975). Early cultivar improvement in Texas consisted primarily of evaluating foreign introductions for their adaptation to Texas soils and climate and making high yielding selections within these cultivars. In 1931, a conventional rice breeding program was established in Texas by the USDA at Substation No. 4 of the Texas Agricultural Experiment Station located near Beaumont. 'Texas Patna' was released in 1942 as the first rice cultivar developed from the program using artificial hybridization. Over the next 50 yr, 26 cultivars were released from this breeding program, many of which were widely grown throughout the southern United States. The released cultivars had improvements in grain yield, maturity, height (semidwarfness), lodging resistance, grain shape, ratoon potential, disease resistance, parboiling and processing quality, milling quality, and grain aroma. The same period saw cultural management improvements in irrigation techniques, pest control measures, and fertilizer applications that have helped to increase grain yields some threefold. (USDA-National Agricultural Statistics Service, 2007).

Progress made through cultivar improvement is usually measured indirectly and is associated with increased food production. Yield increases can be attributed to the combination of genetically improved cultivars and optimized crop management systems (Feil, 1992). Information on the contribution of plant breeding to yield improvement is important in designing strategies to further optimize gains in grain yield (Wych and Stuthman, 1983; Cuevasperes et al., 1995). Moreover, the comparison of the agromorphological traits of old and new cultivars will indicate the breeding value of the germplasm (Feil, 1992). The objective of this study was to determine the contribution of rice breeding efforts to changes in number of days to heading, plant height, whole and total milling percentages, and grain yield of rice cultivars developed across 48 yr of rice breeding efforts in Texas.

MATERIALS AND METHODS

Field experiments were conducted at three environments, which included two plantings (1992 and 1994) at the Texas A&M University System, Agricultural Research and Extension Center (59°57′ N, 94°30′ W) near Beaumont, TX, where the soil is Beaumont, an Entic Pelludert (fine, montmorillonitic, and thermic) and one planting (1993) at the Texas Agricultural Experiment Station (29°37′ N, 96°20′ W) near Eagle Lake, TX, where the soil is a Nada fine sandy loam (fine-loamy, siliceous, active, hyperthermic Albaquic Hapludalfs). Except for genotype and fertilization rate, all productions practices followed the 1992 to 1994 rice production guidelines (Texas Cooperative Extension Service, 1992, 1993, 1994).

Experimental plots were replicated three times in each environment and were arranged in a split-plot design with nitrogen levels as whole plots and cultivars as subplots. Two fertility rates were used to represent cultural management practices that bracketed the 50-yr time span of cultivar development. The two N levels were 95 kg ha^{-1} N (34 kg ha^{-1} N at preflood and 61 kg ha^{-1} N at permanent flood) and 190 kg ha^{-1} N (67 kg ha^{-1} N at preflood and 123 kg ha^{-1} at permanent flood). The lower N rate represents the amount of N recommended to earlier-released rice cultivars, while the higher N rate represents the amount recommended for the later-released cultivars. The 23 Texas cultivars used in this study and their respective year of release are presented in Table 1. The following data were gathered: number of days to heading, plant height, whole and total milled rice percentages, and grain yield. The data were analyzed using SAS (SAS Institute, 2002–2003) with environment (year-location combination) as the main plot, nitrogen as the subplot, and cultivar as the sub-subplot in a split-split plot design. Means were compared using LSD. Mean grain yield and other traits were regressed against year of cultivar release in two N levels to determine the direction and rate of change, that is, the annual increase or decrease that can be attributed to cultivar improvement.

RESULTS AND DISCUSSION

Days to Heading

Cultivar, environment, nitrogen, cultivar × environment, and cultivar × environment × nitrogen had significant effects on number of days to heading (Table 2). Cultivar, environment, and N level explained 71.7, 18.2, and 2.4% of the variation in number of days to heading, respectively, while the two- and three-factors interaction accounted for the remaining 7.7% of the variability. These results indicate that the majority of the variation in heading date can be explained by the genotype, environment, and N application. Absence of interaction of N level with environment and cultivar suggests that specific N level for a particular year or location or cultivar is not critical in the number of days to heading.

The mean number of days to heading of the 23 cultivars in three environments and two N levels is presented in Table 1. Generally, lower N had earlier heading than higher N with 2 to 3 d difference and the Eagle Lake site had earlier heading than the two Beaumont plantings. As expected, the late heading cultivars were always late in three environments and N levels, and early flowering cultivars follow the same trend. This pattern is due to their higher contribution in the total variation of number of days to heading. The mean number of days to heading (averaged across environments and nitrogen levels) ranged from 79 d for 'Maybelle' (released in 1989) to 105 d for Bluebonnet (released in 1944). The mean number of days to heading (averaged across cultivars and nitrogen levels) ranged from 88 d (Eagle Lake, 1992) to 94 d (Beaumont, 1992). Number of days to heading was significantly longer (1.6 d) at 190 kg ha^{-1} N than at the 95 kg ha^{-1} N. For the three-way interaction, Bluebonnet headed the latest at 109 d, and this occurred at Beaumont in 1992 when fertilized with 190 kg^{-1} ha N. In contrast, Maybelle headed

Table 1. Number of days to heading of 23 rice cultivars, released from 1944 to 1992, at three environments and two nitrogen levels.

Year	Released cultivar	No. of days to heading					
		Beaumont, TX, 1992		Eagle Lake, TX, 1993		Beaumont, TX, 1994	
		95 kg ha^{-1} N	190 kg ha^{-1} N	95 kg ha^{-1} N	190 kg ha^{-1} N	95 kg ha^{-1} N	190 kg ha^{-1} N
		d ± SD					
1944	Bluebonnet	107.3 ± 0.58	108.7 ± 0.58	99.3 ± 0.58	101.7 ± 1.53	107.0 ± 1.00	107.0 ± 1.00
1951	Bluebonnet 50	107.0 ± 1.00	109.0 ± 0.00	99.0 ± 1.00	100.7 ± 1.53	106.7 ± 0.58	107.0 ± 1.00
1951	Century Patna 231	96.0 ± 1.00	99.3 ± 0.58	88.3 ± 1.15	92.0 ± 1.73	95.3 ± 0.58	95.0 ± 1.00
1960	Gulfrose	90.3 ± 0.58	91.3 ± 0.58	84.7 ± 0.58	88.3 ± 0.58	88.7 ± 2.31	91.7 ± 0.58
1961	Belle Patna	90.7 ± 4.62	90.3 ± 1.15	81.7 ± 2.08	83.3 ± 1.15	82.7 ± 0.58	86.0 ± 0.00
1965	Bluebelle	93.0 ± 1.00	98.0 ± 2.65	84.7 ± 1.15	88.0 ± 1.73	87.7 ± 1.15	88.7 ± 0.58
1966	Dawn	95.0 ± 1.00	96.7 ± 1.15	86.0 ± 1.00	89.3 ± 0.58	94.7 ± 1.15	93.7 ± 0.58
1972	Labelle	85.3 ± 0.58	87.3 ± 1.53	78.7 ± 1.15	82.3 ± 0.58	82.0 ± 1.00	83.3 ± 1.15
1974	Brazos	90.7 ± 1.15	92.0 ± 0.00	83.3 ± 0.58	85.7 ± 2.08	89.7 ± 0.58	89.7 ± 1.15
1974	Lebonnet	92.3 ± 0.58	95.7 ± 1.15	84.7 ± 2.08	88.3 ± 1.15	88.3 ± 0.58	91.3 ± 0.58
1979	Newrex	92.3 ± 0.58	94.7 ± 3.79	86.3 ± 2.52	90.3 ± 2.31	88.3 ± 1.15	90.7 ± 0.58
1981	Bellemont	94.0 ± 0.00	96.3 ± 1.15	86.3 ± 2.52	88.7 ± 2.31	89.0 ± 0.00	93.7 ± 3.06
1983	Lemont	96.3 ± 1.53	98.7 ± 0.58	85.3 ± 1.15	89.0 ± 0.00	91.7 ± 1.15	95.0 ± 1.00
1983	Pecos	90.3 ± 0.58	91.7 ± 1.15	81.3 ± 1.15	84.0 ± 1.00	88.3 ± 4.04	87.0 ± 1.00
1983	Skybonnet	88.7 ± 1.53	90.3 ± 1.53	81.7 ± 0.58	83.3 ± 0.58	85.7 ± 1.15	87.3 ± 1.15
1986	Gulfmont	89.0 ± 6.08	95.0 ± 0.00	83.7 ± 0.58	88.3 ± 1.15	97.3 ± 1.15	96.3 ± 1.53
1986	Rexmont	97.0 ± 0.00	99.0 ± 1.00	87.0 ± 1.73	89.3 ± 3.51	90.3 ± 3.06	89.0 ± 0.00
1987	Rico 1	92.7 ± 0.58	94.0 ± 0.00	84.3 ± 0.58	89.3 ± 0.58	91.7 ± 2.89	91.7 ± 1.15
1989	Jasmine 85	100.0 ± 0.00	103.3 ± 2.08	95.0 ± 2.00	97.0 ± 0.00	101.3 ± 0.58	104.0 ± 2.65
1989	Maybelle	81.3 ± 0.58	82.3 ± 1.15	72.7 ± 0.58	76.0 ± 0.00	80.3 ± 0.58	81.7 ± 0.58
1990	Texmont	88.0 ± 1.73	90.7 ± 0.58	82.7 ± 1.15	84.3 ± 0.58	83.3 ± 0.58	84.7 ± 0.58
1991	Rosemont	87.7 ± 1.53	90.0 ± 1.00	78.3 ± 1.53	81.7 ± 1.53	84.0 ± 0.00	85.3 ± 0.58
1992	Dellmont	94.7 ± 0.58	97.3 ± 2.08	85.3 ± 1.15	88.7 ± 1.53	88.7 ± 1.53	94.0 ± 3.46
Regression equation of days to heading against year of cultivar release		$Y = 529.8 - 0.22X$**	$Y = 501.9 - 0.21X$*	$Y = 525.6 - 0.22X$**	$Y = 509.1 - 0.21X$**	$Y = 560.2 - 0.24X$*	$Y = 511.1 - 0.21X$*

*Significant linear relationship at the 0.05 probability level.

**Significant linear relationship at the 0.01 probability level.

Table 2. Analysis of variance of the effects of environment (E), nitrogen level (N), cultivar (C), and their interactions on days to heading, plant height (cm), percentages of whole and total milled rice, and grain yield (kg ha^{-1}).

Source of variation	df	Days to heading		Plant height		Whole milled rice percentage		Total milled rice percentage		Grain yield	
		MS	*P*-value	MS	*P*-value	MS	*P*-value	SS	*P*-value	MS	*P*-value
E	2	1927.25	<0.0001	2823.2	0.0001	1718.54	0.0002	614.113	<0.0001	17,650,656	0.0194
Error A†	6	10.60		49.0		33.53		1.805		2,162,992	
N	1	504.47	0.0001	12,446.6	<0.0001	2.48	0.6072	0.443	0.7112	74,248,483	<0.0001
E × N	2	24.03	0.0820	511.1	0.0058	96.77	0.0089	4.115	0.3172	6,139,265	0.0273
Error B‡	6	6.15		37.3		8.44		2.942		881,551	
C	22	691.74	<0.0001	6466.9	<0.0001	173.62	<0.0001	26.213	<0.0001	17,081,908	<0.0001
E × C	44	15.85	<0.0001	53.7	<0.0001	57.93	<0.0001	3.653	<0.0001	2,438,566	<0.0001
N × C	22	3.20	0.0472	81.1	<0.0001	18.33	0.0010	1.352	0.0029	983,276	0.0073
E × N × C	44	3.10	0.0203	24.8	0.0322	9.69	0.1674	0.594	0.5931	1,079,726	0.0001
Rep(E)	6	10.60	<0.0001	49.0	0.0086	33.53	0.0004	1.805	0.0106	2,162,992	0.0004
Residual	264	2.01		16.7		7.89		0.635		501,570	

†Error A is Rep(E).

‡Error B is N × Rep(E).

Table 3. Plant height of 23 rice cultivars, released from 1944 to 1992, at three environments and two nitrogen levels.

Year	Released cultivar	Plant height					
		Beaumont, TX, 1992		Eagle Lake, TX, 1993		Beaumont, TX, 1994	
		95 kg ha^{-1} N	190 kg ha^{-1} N	95 kg ha^{-1} N	190 kg ha^{-1} N	95 kg ha^{-1} N	190 kg ha^{-1} N
		cm ± SD					
1944	Bluebonnet	141.3 ± 0.58	156.3 ± 2.89	132.7 ± 5.51	139.0 ± 5.29	133.7 ± 5.13	150.7 ± 6.66
1951	Bluebonnet 50	128.7 ± 2.52	145.0 ± 4.58	121.3 ± 9.07	138.0 ± 2.65	119.7 ± 2.52	148.3 ± 4.04
1951	Century Patna 231	126.3 ± 5.13	139.3 ± 4.62	121.7 ± 3.79	124.3 ± 1.53	114.7 ± 2.52	135.3 ± 3.21
1960	Gulfrose	112.7 ± 4.04	140.7 ± 8.39	123.0 ± 5.00	127.7 ± 4.51	124.7 ± 4.04	132.7 ± 1.15
1961	Belle Patna	120.0 ± 5.00	138.0 ± 3.46	111.3 ± 3.79	122.3 ± 5.03	114.7 ± 6.11	131.3 ± 1.15
1965	Bluebelle	107.7 ± 6.81	126.0 ± 0.00	102.0 ± 3.00	111.7 ± 2.52	95.0 ± 3.46	111.7 ± 4.04
1966	Dawn	130.0 ± 3.46	139.3 ± 5.86	116.0 ± 5.00	124.3 ± 1.15	115.0 ± 3.00	130.7 ± 1.53
1972	Labelle	110.7 ± 3.06	122.3 ± 2.52	107.0 ± 7.55	115.0 ± 2.00	106.0 ± 6.08	121.3 ± 1.53
1974	Brazos	95.0 ± 3.00	112.7 ± 1.15	101.0 ± 4.36	105.0 ± 1.73	88.3 ± 7.64	103.0 ± 5.29
1974	Lebonnet	112.0 ± 9.17	129.7 ± 9.29	104.0 ± 2.65	109.0 ± 4.00	100.3 ± 1.15	119.3 ± 3.79
1979	Newrex	99.0 ± 3.00	110.0 ± 2.00	95.3 ± 4.04	107.3 ± 1.15	93.0 ± 1.00	110.3 ± 0.58
1981	Bellemont	82.3 ± 3.06	91.3 ± 3.06	81.0 ± 2.00	78.7 ± 1.53	76.7 ± 2.52	79.7 ± 4.04
1983	Lemont	85.3 ± 2.31	95.3 ± 3.06	74.0 ± 1.00	79.0 ± 2.65	75.7 ± 3.06	84.7 ± 3.79
1983	Pecos	100.0 ± 1.73	110.3 ± 10.5	96.7 ± 3.21	102.7 ± 4.04	95.0 ± 6.08	104.7 ± 1.53
1983	Skybonnet	103.7 ± 1.53	120.3 ± 0.58	100.7 ± 0.58	110.3 ± 6.43	99.3 ± 3.06	112.7 ± 2.52
1986	Gulfmont	85.3 ± 4.04	99.3 ± 1.15	78.7 ± 4.62	81.0 ± 2.65	78.0 ± 1.00	83.7 ± 1.53
1986	Rexmont	87.0 ± 2.65	88.7 ± 4.16	77.3 ± 2.52	77.3 ± 3.06	74.7 ± 4.51	85.3 ± 3.21
1987	Rico 1	96.7 ± 4.16	113.7 ± 6.03	94.7 ± 1.53	108.7 ± 5.51	88.0 ± 10.15	108.7 ± 7.77
1989	Jasmine 85	102.7 ± 3.06	107.0 ± 2.65	92.3 ± 7.51	100.0 ± 1.00	103.0 ± 6.08	111.3 ± 2.52
1989	Maybelle	91.0 ± 2.65	101.0 ± 5.20	82.7 ± 2.08	85.3 ± 3.51	89.0 ± 1.73	100.7 ± 1.53
1990	Texmont	82.7 ± 1.15	91.3 ± 6.11	74.7 ± 3.21	77.3 ± 5.86	82.3 ± 5.86	87.0 ± 3.46
1991	Rosemont	78.7 ± 5.77	91.3 ± 3.21	73.0 ± 2.65	78.7 ± 1.53	75.7 ± 2.31	82.3 ± 6.35
1992	Dellmont	83.7 ± 2.08	97.0 ± 4.36	76.3 ± 5.51	84.7 ± 2.08	75.7 ± 3.79	85.7 ± 3.51
Regression equation of plant height against year of cultivar release		$Y = 2291.8 - 1.11X^{**}$	$Y = 2658.3 - 1.29X^{**}$	$Y = 2365.4 - 1.15X^{**}$	$Y = 2528.3 - 1.23X^{**}$	$Y = 2173.9 - 1.05X^{**}$	$Y = 2717.8 - 1.32X^{**}$

**Significant linear relationship at the 0.01 probability level.

the earliest at 73 d, and this occurred at Eagle Lake when fertilized with 95 kg^{-1} ha N.

There was a significant linear relationship between number of days to heading and year of cultivar release in each environment and N level (Table 1). The linear regression model in each N level and environment showed a range of −0.21 to −0.24 d yr^{-1} decrease rate in number of days to heading. The mean number of days to heading for cultivars released from 1944 to 1992 decreased for each N level and environment. The only exception to this was the aromatic cultivar Jasmine 85 that was developed from a cross of indica germplasm at IRRI and selected for adaptation to the southern U.S. rice production area. These results demonstrated that there was a 12- to 18-d decrease in number of days to heading through the 48 yr of rice improvement. Early heading date is still the choice, as demonstrated by the recently released cultivars ('Saber', 'Hidalgo', 'Presidio', and 'Sabine'), which averaged 88 d in 2005 and 79 d in 2006 in the Uniform Regional Rice Nursery (URRN). Breeding for early-maturing cultivars is a universal breeding objective in all U.S. rice breeding programs (Rutger and Bollich, 1991). The maturity of IRRI-released cultivars from 1974 to 1983 shows a decrease by 10 d (Peng et al., 2000).

The reduction in the number of days to heading was a breeding objective at the onset of the rice breeding program in Texas because this trait offered several advantages. An early-maturing cultivar allowed for the growing of a main crop plus a ratoon crop in one cropping season, resulting in a greater grain yield. A second advantage was that an early-maturing cultivar required less irrigation water for its main crop, thereby reducing costs. Third, an early-maturing cultivar reduced the length of time that a crop is exposed to environment, from which adverse biotic (pests) or abiotic (extreme temperature or rainfall) conditions may arise. Avoiding these stresses translated to avoiding additional inputs to manage these potential problems.

Plant Height

Cultivar, nitrogen, and environment and their interactions significantly affected plant height (Table 2). Cultivar and nitrogen effects explained 82.8 and 7.2% of the variation in plant height, respectively. Environment explained 3.3%, and each of the interactions contributed less than 1.4% of the variation in plant height. Similar to heading, plant height was primarily due to cultivar, nitrogen level, and environment. Although all the interactions were significant, these were far less important than the above three sources of variations.

The mean plant height of 23 cultivars in each environment and N level is shown in Table 3. Generally, at Beaumont and Eagle Lake, taller plants were obtained at higher N level, and earlier cultivar releases were taller than later cultivar releases. Mean cultivar plant height (averaged across environments and N levels) ranged from 79.9 cm for 'Rosemont' (released in 1991) to 142.3 cm for Bluebonnet. Mean plant height (110.9 cm) at the 190 kg ha^{-1} N level was significantly higher than that 99.7 cm at the 95 kg ha^{-1} N level. Mean plant height at the 1992 Beaumont environment (110.3.8 cm) was significantly higher than at both the 1994 Beaumont (103.8 cm) and 1993 Eagle Lake (101.7 cm) environments. Considering the interaction, the tallest was Bluebonnet (156.3 cm) planted at Beaumont in 1992 and fertilized with 190 kg ha^{-1} N, and the shortest was Rosemont (73.0 cm) planted in Eagle Lake with 95 kg ha^{-1} N.

Table 4. Whole milled rice percentages of 23 rice cultivars, released from 1944 to 1992, at three environments.

Year	Released cultivar	Whole milled rice		
		Beaumont, TX, 1992	Eagle Lake, TX, 1993	Beaumont, TX, 1994
		% ± SD		
1944	Bluebonnet	53.8 ± 1.90	55.0 ± 5.33	47.1 ± 2.74
1951	Bluebonnet 50	58.4 ± 1.20	56.5 ± 3.27	51.5 ± 2.92
1951	Century Patna 231	61.5 ± 1.83	61.2 ± 4.79	58.3 ± 2.27
1960	Gulfrose	66.1 ± 1.41	65.5 ± 1.38	55.7 ± 2.74
1961	Belle Patna	58.4 ± 2.38	62.2 ± 3.19	49.1 ± 2.23
1965	Bluebelle	57.7 ± 1.75	60.0 ± 7.01	57.1 ± 0.84
1966	Dawn	53.6 ± 4.19	62.5 ± 3.27	55.4 ± 0.82
1972	Labelle	62.0 ± 2.61	65.2 ± 2.40	51.6 ± 3.44
1974	Brazos	64.4 ± 2.55	66.0 ± 0.63	57.4 ± 2.16
1974	Lebonnet	60.5 ± 2.04	64.7 ± 2.07	58.2 ± 3.25
1979	Newrex	55.9 ± 2.41	62.5 ± 1.64	52.1 ± 0.91
1981	Bellemont	58.5 ± 4.22	64.0 ± 2.10	60.1 ± 3.17
1983	Lemont	58.5 ± 4.12	65.3 ± 2.42	60.2 ± 1.96
1983	Pecos	66.1 ± 1.92	64.2 ± 5.53	62.5 ± 2.65
1983	Skybonnet	60.1 ± 2.18	61.2 ± 4.92	59.3 ± 1.23
1986	Gulfmont	59.8 ± 3.14	65.2 ± 2.48	60.3 ± 3.08
1986	Rexmont	51.7 ± 7.16	62.8 ± 1.17	53.4 ± 2.00
1987	Rico 1	66.0 ± 0.86	60.3 ± 5.01	52.2 ± 1.97
1989	Jasmine 85	56.8 ± 3.07	55.7 ± 2.88	46.0 ± 7.24
1989	Maybelle	60.3 ± 1.87	65.0 ± 2.45	52.3 ± 2.90
1990	Texmont	55.1 ± 3.39	61.7 ± 3.08	55.0 ± 1.88
1991	Rosemont	51.9 ± 4.28	63.7 ± 2.66	58.0 ± 1.87
1992	Dellmont	60.1 ± 1.65	64.8 ± 3.66	60.2 ± 1.53
Regression equation of whole milled rice against year of cultivar release		$Y = 78.5 - 0.0099X^{**}$	$Y = -116.0 + 0.0903X^{\dagger}$	$Y = -132.8 + 0.0952X^{**}$

**Significant linear relationship at the 0.01 probability level.

†*P*-value = 0.053.

There was a significant linear decrease in plant height of cultivars released from 1944 to 1992 in each environment and N level (Table 3). The average plant height decrease rates were −1.11 cm yr^{-1} for the 95 kg ha^{-1} N level and −1.29 cm yr^{-1} for 190 kg ha^{-1} N level at Beaumont in 1993, and nearly as much in 1994. At Eagle Lake, the average plant height decrease rates were −1.15 cm yr^{-1} and −1.23 cm yr^{-1} at the 95 and 190 kg ha^{-1} N levels, respectively. There were differences in the slope of the lines between the two N levels (0.08 to 0.27) in three environments; these differences demonstrate that under the higher N inputs that are common today, the cultivars lacking the *sd-1* gene respond more dramatically to fertilizer (and would be more susceptible to lodging) than semidwarf cultivars.

As early as 1966, scientists at IRRI discovered that plant architecture of traditional cultivars was the main constraint in increasing grain yield. This plant type lodged especially at high N application levels but can yield well if supported to stand. The first decade of breeding at IRRI was focused on dwarfism (Peng and Khush, 2003) and the development of IR8, the dwarf high-yielding cultivar that triggered the so-called Green Revolution. IR8, 'Deo-geo-woo-gen', and 'Taichung Native' (TN1), all carrying the *sd-1* gene, were the main sources of semidwarfism in U.S. breeding programs (Rutger and Bollich, 1991). In Texas, the first semidwarf cultivar with the *sd-1* gene from TN1 was 'Bellemont', released in 1981 (Bollich et al., 1983). This was quickly replaced by the release in 1983 of the semidwarf 'Lemont', which was the first widely grown semidwarf cultivar in the southern United States. Lemont and its sister line, 'Gulfmont' (released in 1986), remained as cornerstones to the rice industry for over 20 yr. With the development of DNA markers for the *sd-1* gene and its eventual use by breeders, the observed change in plant height over the coming years will likely not decrease much further.

Table 5. Whole milled rice percentages of 23 rice cultivars, released from 1944 to 1992, at two N levels.

Year	Released cultivar	Whole milled rice	
		95 kg ha^{-1} N	190 kg ha^{-1} N
		% ± SD	
1944	Bluebonnet	51.5 ± 6.19	52.4 ± 3.62
1951	Bluebonnet 50	55.1 ± 4.62	55.9 ± 3.22
1951	Century Patna 231	60.7 ± 3.49	60.0 ± 3.43
1960	Gulfrose	63.0 ± 4.47	61.9 ± 6.18
1961	Belle Patna	56.4 ± 6.47	56.7 ± 6.21
1965	Bluebelle	57.2 ± 4.04	59.4 ± 4.17
1966	Dawn	57.1 ± 3.71	57.2 ± 6.13
1972	Labelle	59.8 ± 7.77	59.3 ± 5.54
1974	Brazos	63.3 ± 4.56	61.8 ± 4.09
1974	Lebonnet	61.9 ± 1.58	60.4 ± 4.91
1979	Newrex	56.9 ± 4.27	56.8 ± 5.37
1981	Bellemont	62.5 ± 1.62	59.2 ± 4.83
1983	Lemont	60.5 ± 3.91	62.2 ± 4.32
1983	Pecos	65.9 ± 1.84	62.6 ± 4.61
1983	Skybonnet	59.9 ± 2.59	60.4 ± 3.68
1986	Gulfmont	61.4 ± 3.43	62.1 ± 4.14
1986	Rexmont	56.6 ± 4.36	55.3 ± 8.34
1987	Rico 1	60.5 ± 6.94	58.5 ± 6.32
1989	Jasmine 85	50.3 ± 7.62	55.4 ± 4.90
1989	Maybelle	57.7 ± 6.31	60.6 ± 5.37
1990	Texmont	56.1 ± 3.59	58.4 ± 4.64
1991	Rosemont	58.3 ± 4.29	57.4 ± 7.15
1992	Dellmont	60.6 ± 2.65	62.8 ± 3.55
Regression equation of whole milled rice against year of cultivar release		$Y = -41.2 + 0.0506X$	$Y = -72.4 + 0.0665X$

A relatively shorter plant height was targeted early in the Texas rice breeding program as this offered several advantages. Shorter plants reduced lodging, particularly under high N inputs, a higher plant population could be planted, and a higher harvest index could be obtained; all these translated to relatively higher yield. Moreover, the mean plant height of recently released cultivars (Saber, Hidalgo, Presidio, and Sabine) was 95 cm in 2005 and 96 cm in 2006 in the URRN.

Whole Milled Rice Percentage

Cultivar, environment, cultivar × environment, cultivar × nitrogen, and nitrogen × environment had significant effects on whole milled rice percentage (Table 2). The amount of variation in whole milled rice percentage that these factors explained was 28.6, 25.7, 19.1, 3.0, and 1.4%, respectively. There was no significant difference in whole milled rice percentage when fertilized with 95 or 190 kg ha^{-1} N.

Whole milled rice percentage of long grain cultivars (averaged across environments and nitrogen levels) ranged from 51.9% for Bluebonnet (released in 1944) to >61.7% for Gulfmont and 'Dellmont'. The medium grain cultivar Gulfrose (released in 1960) averaged 62.4% milling yield compared with 59.5% milling for 'Rico 1' (released in 1987). Although there was slight decrease in whole milled rice percentage between these two cultivars released 27 yr apart, Rico 1 produced significantly higher main crop yield, resulting in much higher whole milled rice produced per hectare. There were significant differences between each of the environments in terms of whole milled rice percentage. Mean whole milled rice percentage ranged from 55.3% for the 1994 Beaumont environment to 62.4% for 1993 Eagle Lake. Whole milled rice percentages of 23 cultivars in three environments and two N levels are shown in Tables 4 and 5. Highest whole milled rice percentage was obtained in Gulfrose and 'Pecos' (66.1%) planted in Beaumont in 1992, and the lowest was from Bluebonnet (47.1%) grown in Beaumont in 1994. The environment and its highly significant interaction with cultivar and N levels demonstrated the sensitivity of this trait to environmental fluctuations. For nitrogen and cultivar interaction, the highest whole milled rice percentage was again produced by Pecos, and the lowest was still produced by Bluebonnet, but both were obtained at lower N level. These results showed the differential response of cultivars to varying N levels in the quality of milled rice.

There were positive linear relationships between whole milled rice percentage and year of cultivar release when analyzed in three environments (Table 4) and two nitrogen levels (Table 5), but not all were significant. These relationships, however, still indicate the contribution of breeding to the improvement of this trait, as whole milled rice percentages increased from Bluebonnet to Dellmont. In two environments, the rate of increase in whole milled rice percentage was at least 0.09% yr^{-1}, while the rates of 0.05 and 0.07% yr^{-1} were estimated for the 95 and 190 kg ha^{-1} N levels, respectively. On average, the rate of increase in whole milled rice percentage was estimated at 0.06% yr^{-1}. In comparison, the mean whole milled rice percentage of recently released cultivars (Saber, Hidalgo, Presidio, and Sabine) in the URRN was 54% in 2005 and 64% in 2006, demonstrating that genetic advances for some traits can be overwhelmed by environmental conditions.

Whole milled rice percentage is an important factor in determining the market value of milled rice. It is included as one of the breeding objectives, along with the improvement of other grain quality traits such as amylose content, alkali spreading value, and gel consistency, which relate to eating quality. With the identification of quantitative trait loci for this trait (Tan et al., 2001; Aluko et al., 2004) and the development of DNA markers that expedite selection, the current high level of whole milled rice percentage can be maintained in future cultivars, and there is increased likelihood that genotype × environment factors that impact milling can be better understood.

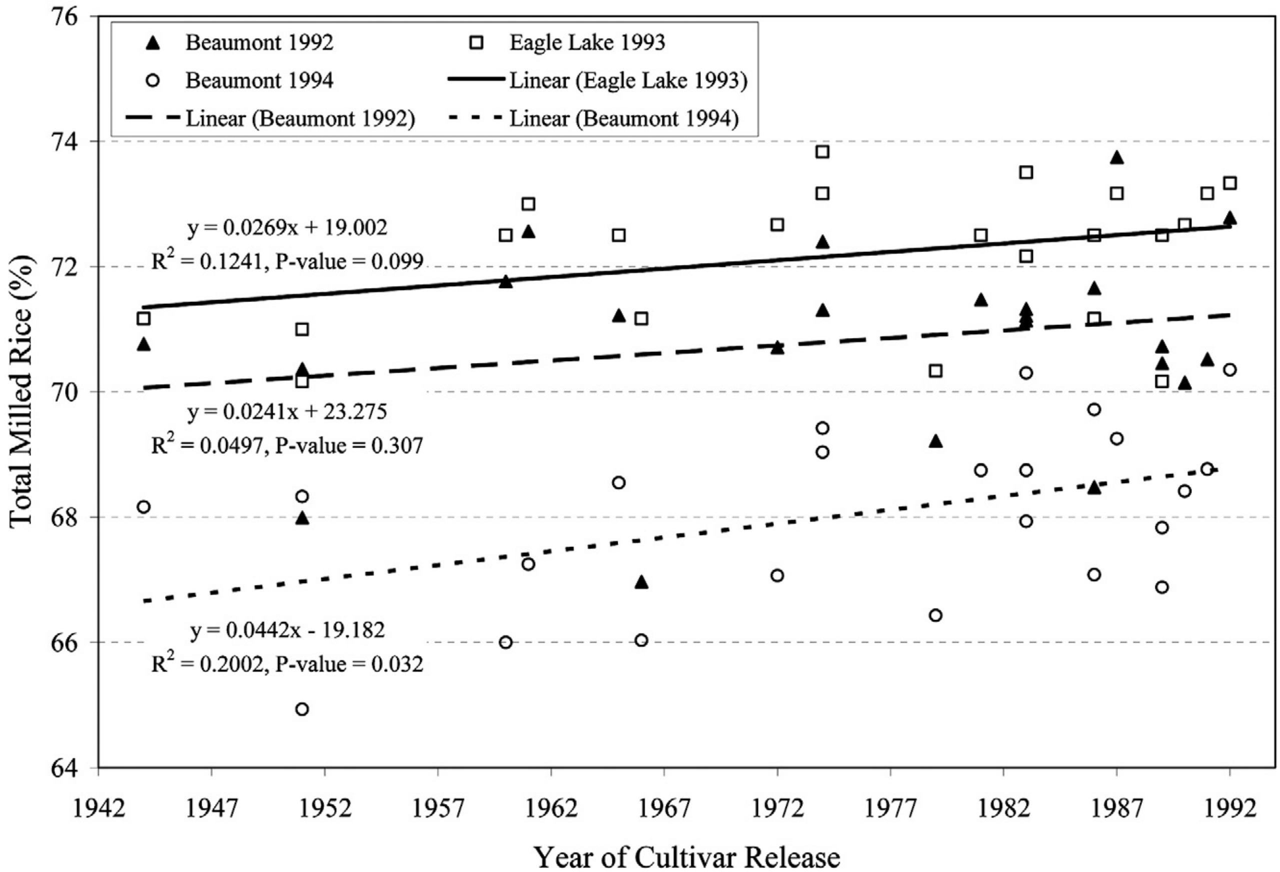

Figure 1. Relationship between total milled rice percentage and year of cultivar release of 23 rice cultivars when grown at three environments in Texas.

Total Milled Rice Percentage

Environment, cultivar, cultivar × environment, and cultivar × nitrogen had significant effects on total milled rice percentage (Table 2). The amount of variation in total milled rice percentage that these factors explained was 54.9, 25.8, 7.2, and 1.3%, respectively. Of the traits measured, only whole and total milling yield had such high proportion of the variance explained by the environment. There was no significant difference in total milled rice percentage when fertilized with 95 or 190 kg ha^{-1} N.

There were significant differences between each of the environments in terms of total milled rice percentage. Mean total milled rice percentage ranged from 68.0% for the 1994 Beaumont environment to 72.2% for the 1993 Eagle Lake environment. The total milled rice percentage of cultivars (averaged across environments and N levels) ranged from 67.7% for 'Century Patna 231' (released in 1951) to 72.2% for Dellmont. Across N levels, the highest total milled rice was obtained in 'Brazos' (73.8%) grown at Eagle Lake, while the lowest was from Century Patna 231 (64.9%) grown in Beaumont, 1994. Across locations, the highest was from Rico 1 and Delmont (72.2%) fertilized with 95 kg ha^{-1} N, and the lowest was from Century Patna 231 (67.6%) applied with 95 kg ha^{-1} N. These results showed that cultivar response in total milled rice percentage varies with location and N levels.

Regression analysis in three environments showed significant linear relationship between total milled rice percentage and year of cultivar release (Fig. 1) in Beaumont, 1994, and at higher N level, but the rates of increase in total milled rice percentage from Bluebonnet (70.0%) to Dellmont (72.2%) were generally small. The average rate of increase for total milled rice percentage in three environments was estimated at 0.03% yr^{-1}. A similar trend, the slow increase rate in total milled rice percentage across years, was noted in the regression analysis in two N levels (Fig. 2). By comparison, the mean total milled rice percentage of recently released cultivars (Saber, Hidalgo, Presidio, and Sabine) in the URRN was 68% in 2005 and 72% in 2006.

Most of the previous studies reported in the literature were conducted to determine the contribution of cultivar improvement to yield and agronomic traits (Tollenaar, 1989; Babcock and Foster, 1991; Feil, 1992; Casler et al., 2000; Peng et al., 2000; Abeledo et al., 2003; Kawano, 2003; Nersting et al., 2006). In rice, none dealt with milled rice percentage traits. This is the first study to show the progress made in increasing whole and total milled rice percentages through breeding. Both milling traits are critical to millers since they determine milling yield on a farmer's crop before they determine the price or premium that they are willing to pay. A cultivar with high whole

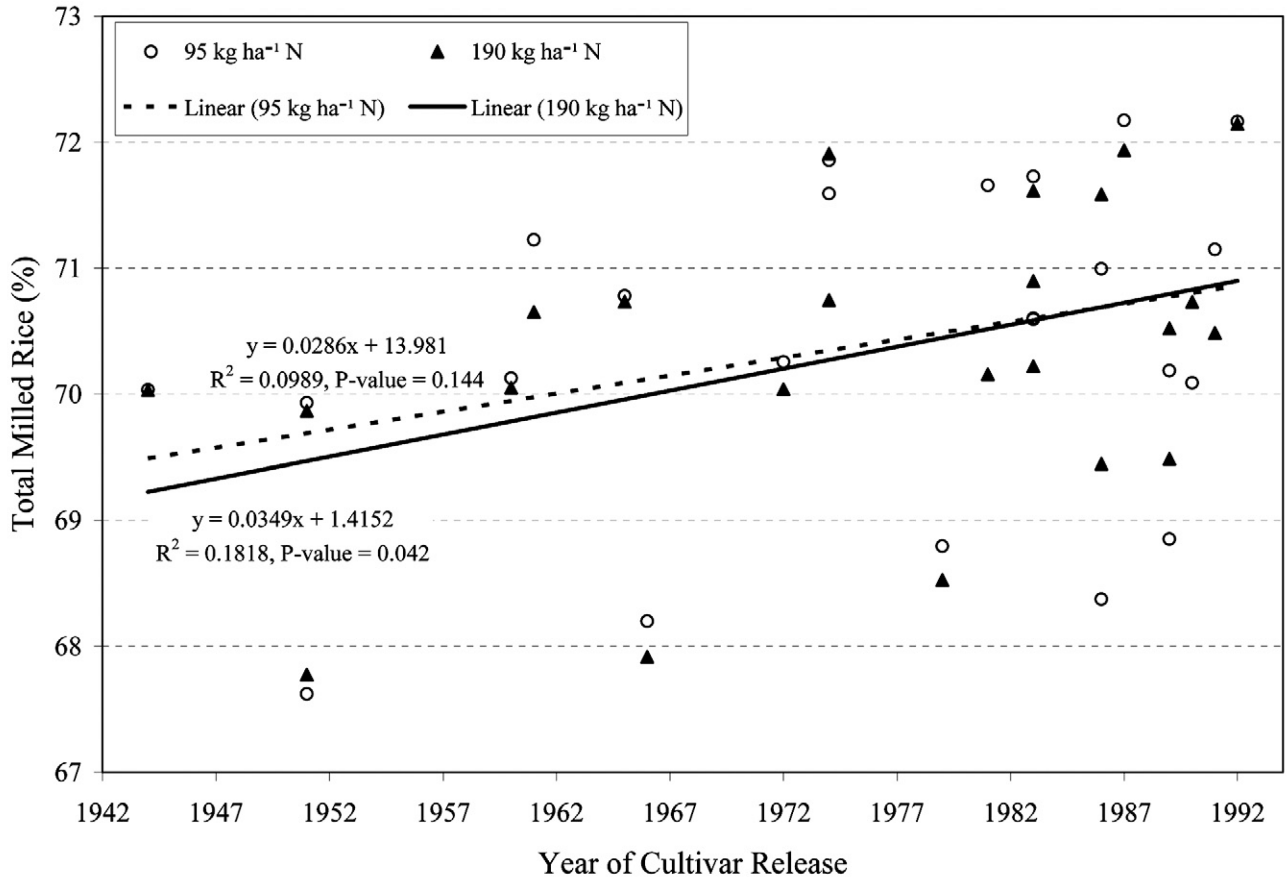

Figure 2. Relationship of total milled rice percentage and year of cultivar release of 23 rice cultivars when grown at two nitrogen fertilization levels.

and total milled rice percentages is important for protecting the interests of producers, millers, and consumers.

Grain Yield

Cultivar, cultivar × environment, nitrogen, cultivar × environment × nitrogen, environment, cultivar × nitrogen, and nitrogen × environment had significant effects on grain yield (Table 2). The amount of variation in grain yield that they explained was 44.9.1, 12.8, 8.9, 5.7, 4.2, 2.6, and 1.5%, respectively.

Table 6 shows the mean yield of the 23 rice cultivars grown in three environments and two N levels. The grain yield of cultivars (averaged across environments and N levels) ranged from 4902 kg ha^{-1} for Century Patna 231 to 8565 kg ha^{-1} for Jasmine 85 (released in 1989). Grain yield (averaged across environments and cultivars) was 5646 kg ha^{-1} when fertilized with 95 kg ha^{-1} N and 6492 kg ha^{-1} when fertilizer with 190 kg ha^{-1} N. Grain yield (averaged across cultivars and N levels) was significantly higher at the 1993 Eagle Lake environment (6466 kg ha^{-1}) than at the 1994 Beaumont environment (5969 kg ha^{-1}), which in turn was significantly higher than the 1992 Beaumont environment (5772 kg ha^{-1}). Considering the significant interactions, the highest yield was obtained from Jasmine 85 (9583 kg ha^{-1}) grown in Beaumont in 1994 and applied with 190 kg ha^{-1} N, and the lowest was from Century Patna (3588 kg ha^{-1}) from Eagle Lake and applied with 95 kg ha^{-1} N. The significant cultivar × environment and three-way interactions indicated that specific genotypes yielded better at specific environments and N levels. This also implied that genotype × environment interaction and fertilizer response should be considered when making cultivar selections or recommendations using multi-environment trials data.

There was a significant linear increase in the grain yield of rice cultivars released from 1944 to 1992 when fertilized with 190 kg ha^{-1} N at the Eagle Lake and Beaumont 1994 environments (Table 6). Regression analysis of grain yield and year of release in three environments and two N levels showed rate of yield increase ranged from 17.7 to 69.1 kg yr^{-1}. The rate of grain yield increase that was due to the breeding of new cultivars was 42 kg yr^{-1} at 190 kg ha^{-1} N and 26.3 kg yr^{-1} at 95 kg ha^{-1} N. The positive slope of both of these lines demonstrated that breeding has resulted in higher intrinsic yield potential regardless of fertilizer inputs. Mean grain yields increased from 5599 kg ha^{-1} for Bluebonnet to 6570 kg ha^{-1} for Dellmont. The breeding for high yield continues to be a primary objective in the improvement of rice cultivars. Recently released cultivars (Saber, Hidalgo, Presidio, and Sabine) produced grain yields of 9215 kg ha^{-1} in 2005 and 9140 kg ha^{-1} in 2006 in the URRN at Beaumont, TX.

Table 6. Grain yield of 23 rice cultivars, released from 1944 to 1992, at three environments and two nitrogen levels.

Year	Released cultivar	Grain yield					
		Beaumont 1992		Eagle Lake 1993		Beaumont 1994	
		95 kg ha^{-1} N	190 kg ha^{-1} N	95 kg ha^{-1} N	190 kg ha^{-1} N	95 kg ha^{-1} N	190 kg ha^{-1} N
		kg ha^{-1} ± SD					
1944	Bluebonnet	5284 ± 122	6403 ± 149	5502 ± 1272	6729 ± 966	4885 ± 218	4793 ± 310
1951	Bluebonnet 50	5415 ± 559	5224 ± 409	5872 ± 819	6786 ± 665	5076 ± 274	4987 ± 90
1951	Century Patna 231	4965 ± 866	5317 ± 714	3588 ± 1597	5479 ± 764	5204 ± 875	4860 ± 162
1960	Gulfrose	4734 ± 735	5059 ± 489	3988 ± 443	5136 ± 704	6207 ± 589	4445 ± 1068
1961	Belle Patna	5035 ± 296	5605 ± 223	5110 ± 437	6204 ± 812	4710 ± 591	5564 ± 404
1965	Bluebelle	5313 ± 224	5629 ± 343	5225 ± 1490	7224 ± 652	4628 ± 336	6104 ± 296
1966	Dawn	5169 ± 571	5192 ± 554	5370 ± 940	6615 ± 584	5637 ± 412	5967 ± 523
1972	Labelle	5425 ± 128	5109 ± 757	4485 ± 131	6000 ± 846	5094 ± 134	5183 ± 221
1974	Brazos	6349 ± 1234	6595 ± 1069	7830 ± 878	8642 ± 1016	5506 ± 1687	7267 ± 204
1974	Lebonnet	5882 ± 680	5997 ± 598	7002 ± 401	7771 ± 1143	5894 ± 362	6013 ± 231
1979	Newrex	5244 ± 363	5947 ± 429	4277 ± 1092	6256 ± 888	4470 ± 166	6309 ± 979
1981	Bellemont	4556 ± 622	4907 ± 754	6044 ± 696	6239 ± 685	4439 ± 394	5516 ± 2046
1983	Lemont	5375 ± 943	6336 ± 1005	7252 ± 277	7606 ± 207	5510 ± 411	7487 ± 308
1983	Pecos	6231 ± 369	7008 ± 353	7873 ± 322	7846 ± 889	5930 ± 1569	7161 ± 166
1983	Skybonnet	4839 ± 314	5529 ± 429	4746 ± 998	6425 ± 549	6042 ± 396	6447 ± 79
1986	Gulfmont	5539 ± 152	6423 ± 873	7390 ± 981	8221 ± 423	4036 ± 479	7027 ± 1263
1986	Rexmont	4256 ± 293	4392 ± 2046	6772 ± 499	7009 ± 1223	4547 ± 583	7611 ± 273
1987	Rico 1	8882 ± 745	9449 ± 551	8535 ± 373	8545 ± 335	6599 ± 2341	8853 ± 814
1989	Jasmine 85	8631 ± 219	8094 ± 494	7543 ± 1813	9015 ± 684	8523 ± 597	9583 ± 692
1989	Maybelle	5980 ± 720	6001 ± 84	3730 ± 501	5355 ± 373	5954 ± 792	6485 ± 541
1990	Texmont	5130 ± 209	5517 ± 236	4929 ± 711	7383 ± 331	5475 ± 391	7382 ± 245
1991	Rosemont	5035 ± 399	4722 ± 589	5668 ± 294	7369 ± 360	6109 ± 524	6332 ± 882
1992	Dellmont	5292 ± 93	6506 ± 302	6771 ± 561	8094 ± 69	5033 ± 361	7724 ± 379
Regression equation of grain yield against year of cultivar release		$Y = -36{,}700 + 21.4X$	$Y = -35{,}457 + 21.0X$	$Y = -72{,}732 + 39.8X$	$Y = -61{,}887 + 34.9X$*	$Y = -29{,}431 + 17.7X$	$Y = -130{,}047 + 9.1X$**

*Significant linear relationship at the 0.05 probability level.

**Significant linear relationship at the 0.01 probability level.

The significant effect of N on grain yield showed the N-responsiveness of the released cultivars. Doubling the N applied from 95 to 190 kg ha^{-1} N nearly doubled the rate of yield increase from 26.3 to 42.0 kg ha^{-1} yr^{-1}. This illustrated the impact that breeding has had on developing cultivars that can respond favorably to additional fertilizer inputs when they are applied.

The increasing linear trend in grain yield in Texas cultivars since 1944 followed the changes that have been reported in rice and other crops (Tollenaar, 1989; Babcock and Foster, 1991; Feil, 1992; Casler et al., 2000; Peng et al., 2000; Abeledo et al., 2003; Kawano, 2003; Nersting et al., 2006). Rice breeding at IRRI since the 1966 release of the "miracle rice," IR8, had an annual linear grain yield increase of 75 to 81 kg ha^{-1}. Although the estimated rate of grain yield increase in Texas breeding was only half that, the highest-yielding rice cultivars released in Texas during the last 48 yr (i.e., Rico 1 and Jasmine 85) was very close to 9 to 10 t ha^{-1}, which is the yield potential reported for rice in the tropics (Peng et al., 1999). Moreover, the estimates done at IRRI included the most recent elite lines called 'NPT' (new plant type) that were expected to break the yield barrier set at 10 t ha^{-1} (Peng and Khush, 2003). Likewise, if the current Texas cultivar releases like Presidio were included, a higher rate of grain yield increase for Texas rice breeding would be evident.

The contribution of cultivar development and its impact in increasing food production in the world, particularly in rice and wheat, is well documented but rarely quantified. The introduction of dwarf wheat and rice that doubled food production in several countries and known as the "Green Revolution" has been the prime example, but N application in combination with cultivars had a major role making this revolution possible. With the increasing world population and changing demand for rice, the primary mission of breeders to develop high-yielding cultivars must be continued in conjunction with other breeding objectives to produce high-quality rice as well as improve tolerances to biotic and abiotic stresses that will reduce economic losses and reduce input costs. Associated production technology has to be developed to meet the need for both quantity and quality products. Advances in biotechnology will enhance the incorporation of desirable traits, and further improve the yield and quality of rice. Use of new germplasm such as wild rices and landraces, untouched in several genebanks, coupled with hybrid and idiotype breeding for super rice and super hybrids will increase yield beyond any limitation observed in using the current germplasm and released cultivars.

CONCLUSIONS

The contribution of rice improvement on cultivars released in Texas from 1944 to 1992 showed patterns similar to other crops and rice breeding programs, but the rates varied. Grain yield increased linearly during the period evaluated at 42 kg ha^{-1} yr^{-1} under the 190 kg ha^{-1} N level and 26.3 kg ha^{-1} yr^{-1} under the 95 kg ha^{-1} N level. During the same period, milling traits had significant improvements. Whole milled rice percentage increased at linear rate of 0.06% yr^{-1}, while total milled rice percentage linearly increased at 0.03% yr^{-1}. As for most cereal crops, plant height of rice cultivars released in Texas decreased linearly at the rate of 1.11 cm yr^{-1} and 1.28 cm yr^{-1} for the 95 and 190 kg ha^{-1} N levels, respectively. Furthermore, selection favored the much earlier maturing genotypes, resulting in cultivars with maturities of 12 to 18 d less than the Bluebonnet rice cultivar. These results demonstrate the significant progress that has been achieved in rice breeding for the southern U.S. during the last 48 years since 1944.

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